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F/A-18(A-D) wing root Fatigue Life Expended (FLE) prediction without the use of strain gage data

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THESIS

F/A-18(A-D) WING ROOT FATIGUE LIFE EXPENDED (FLE) PREDICTION WITHOUT THE USE OF STRAIN GAGE DATA

by

Jason M. Lindauer

June 2010

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U.S. Navy and Marine Corps F/A-18 aircraft are subject to two life-limiting metrics—actual flight hours and fatigue life expended (FLE). While flight hours can be mitigated, fatigue on the airframe cannot. The fatigue expended per flight varies based on the mission; it is recorded by seven strain gages throughout the airframe.

Because strain gages are unmonitored systems, they are subject to drift and/or failure. Consequently, Naval Air Systems Command (NAVAIR) accumulates approximately a month of strain gage data for each Navy and Marine Corps F/A-18 before analyzing the data for such anomalies. This results in a latency period of roughly six weeks between the mission being flown and the squadron receiving the FLE for that mission. This research identifies regression models by which to predict the NAVAIR reported FLE using real-time metrics stored by the aircraft during flight, thereby, eliminating the latency issue and allowing squadrons to better manage their aircraft. This research shows that the NAVAIR FLE number can be accurately predicted (adjusted $R^2 \approx 0.95$) using in-flight metrics, such as weight-off-wheels time, minimum g, maximum g, and wing root trigger events.

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F/A-18(A-D) WING ROOT FATIGUE LIFE EXPENDED (FLE) PREDICTION WITHOUT THE USE OF STRAIN GAGE DATA

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ABSTRACT

U.S. Navy and Marine Corps F/A-18 aircraft are subject to two life-limiting metrics—actual flight hours and fatigue life expended (FLE). While flight hours can be mitigated, fatigue on the airframe cannot. The fatigue expended per flight varies based on the mission; it is recorded by seven strain gages throughout the airframe.

Because strain gages are unmonitored systems, they are subject to drift and/or failure. Consequently, Naval Air Systems Command (NAVAIR) accumulates approximately a month of strain gage data for each Navy and Marine Corps F/A-18 before analyzing the data for such anomalies. This results in a latency period of roughly six weeks between the mission being flown and the squadron receiving the FLE for that mission. This research identifies regression models by which to predict the NAVAIR reported FLE using real-time metrics stored by the aircraft during flight, thereby, eliminating the latency issue and allowing squadrons to better manage their aircraft. This research shows that the NAVAIR FLE number can be accurately predicted (adjusted $R^2 \approx 0.95$) using in-flight metrics, such as weight-off-wheels time, minimum g, maximum g, and wing root trigger events.

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EXECUTIVE SUMMARY

U.S. Navy and Marine Corps F/A-18 aircraft are subject to two life-limiting metrics—actual flight hours and fatigue life expended (FLE). While flight hours can be managed by decreasing mission duration, fatigue on the airframe cannot. The FLE per flight varies based on the mission; it is recorded by seven strain gages throughout the airframe. It has been found that the wing root absorbs the most stress (or loading), during maneuvering. Therefore, the wing root strain gage creates the metric that determines the FLE for each Marine Corps F/A-18.

Because strain gages are unmonitored systems, they are subject to drift and/or failure. Consequently, Naval Air Systems Command (NAVAIR) accumulates approximately a month of strain gage data for each Navy and Marine Corps F/A-18 before analyzing the data for such anomalies. This results in a latency period of roughly six weeks between the mission being flown and the squadron receiving the FLE for that mission. Given that an airframe is retired once it reaches a FLE of 1.0, it is imperative that aircraft be aggressively managed in order to achieve maximum airframe life. Because of this, Boeing has created software to be utilized by each Marine Corps squadron that will report a real-time FLE number using data stored by the aircraft during flight. The only piece missing from this software is the prediction models.

This research creates the models for the Boeing software based upon a FLE study data set supplied by NAVAIR. The data set contains both Navy and Marine Corps flight records with corresponding hand-paired FLE results. Because Navy mission codes differ from Marine Corps mission codes, it is necessary to group the records into 11 different mission type codes (MTC's). A regression model is then created for each MTC, as well as for the entire data set. This research shows that the NAVAIR FLE number can be accurately predicted (adjusted $R^2 \approx 0.95$) using in-flight metrics, such as weight-off-wheels time, minimum g, maximum g, and wing root trigger events.

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	Air-to-Air
AAW	Anti-Air Warfare
AFH	Actual Flight Hour
AS	Air-to-Surface
ASLMP	Airframe Service Life Monitoring Program
CAS	Close Air Support
CL	Center Line
CRC	Critical Reference Condition
DSU	Data Storage Unit
dWR	Predicted NAVAIR WRFLE Number
dWRFill	Boeing Algorithm Generated WRFLE Number
FAM	Familiarization Flight
FCF	Functional Check Flight
FCLP	Field Carrier Landing Practice
FERRY	Ferry or Escort Flight
FH	Flight Hour
FLE	Fatigue Life Expended
FLIR	Forward Looking Infrared
FLS	Fatigue Life Standard
FRS	Fleet Readiness Squadron
LAT	Low Altitude Tactics
LH	Left Hand
LSS	Left Store Station

LWO	Left Wing Ordinance
JSF	Joint Strike Fighter
MC	Mission Computer
MFC	Mission Family Code
MTC	Mission Type Code
MSMP2	Mission Severity Monitoring Program 2
NAVAIR	Naval Air Systems Command
NAVFLIR	Naval Aviation Flight Record
NS	Night Systems
Nz	Gravitational Unit
NzW	Boeing Algorithm to Calculate FLE
rDHCnt	Weight Off Wheels Time
rNzMax	Maximum G's (divided by 7.5)
rNzMin	Minimum G's (divided by 7.5)
RBM	Reference Bending Moment
RH	Right Hand
RSE	Residual Standard Error
SAFE	Structural Appraisal of Fatigue Effects
SDC	Signal Data Computer
SLMP	Service Life Management Program
SFH	Spectrum Flight Hour
SS	Sums of Squares
STK	Strike
T&R	Training and Readiness
TMS	Type Model Series

USN	United States Navy
USMC	United States Marine Corps
VGH	Velocity, Gravity, Height
WRFLE	Wing Root Fatigue Life Expended
WRTrigCnt	Wing Root Triggers Outside Deadband

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I. INTRODUCTION

A. BACKGROUND

Operating as an all-weather carrier-capable multirole fighter jet since the early 1980s, the McDonnell Douglas (now Boeing) F/A-18 Hornet is an asset critical to both the U.S. Navy (USN) and Marine Corps (USMC). The flexibility of sea- or shore-basing allows the services to maximize the effectiveness of the aircraft in its primary missions of fighter escort, fleet air defense, suppression of enemy air defenses, interdiction, close air support, and reconnaissance during both peacetime and combat.

The F/A-18 has been through several upgrades. The current model, produced by Boeing, is the F/A-18E/F Super Hornet. The Navy is under contract to replace its aging fleet of F/A-18C/D's with Super Hornets, but the Marine Corps is not. Rather, the Corps looks to (and continues to count on) the Joint Strike Fighter (JSF) to replace its Hornet fleet. The lack of new airframes in the Marine Corps is beginning to adversely affect both fleet and training squadrons, as hours and Fatigue Life Expended (FLE) continue to accrue on each airframe.

The F/A-18 is subject to two airframe life-limiting metrics as published by the Naval Air Systems Command (NAVAIR): total airframe hours and FLE. Currently, the "C" and "D" model Hornets that the Marine Corps operates are limited to 8,000 Actual Flight Hours (AFH) and 6,000 Spectrum Flight Hours (SFH), with the latter being the original design parameter of the aircraft. The 8,000 AFH can be increased to 8,600 based on a high flight-hour inspection, but the Corps is pushing for a further extension to 10,000 AFH due to the unknown fielding date of the JSF. However, even if the AFH extension is approved, the FLE life per airframe cannot be extended. This makes FLE management the most important factor in maximizing airframe life. The research in this thesis aids FLE management by developing models that will be used by the Marine Corps to predict FLE for the F/A-18 in real-time.

1. Structural Life Management Program (SLMP) and Structural Appraisal of Fatigue Effects (SAFE)

To prevent loss of life and/or aircraft due to flight stress on airframes, NAVAIR employs the multifaceted Structural Life Management Program (SLMP). This program keeps track of the day-to-day wear and strain placed on each aircraft in the USN and USMC inventory. The SLMP, consisting of Design, Demonstrate, Track, and Retire processes, is the decision tool used to determine the lifespan of an airframe (Claus, 2009).

Specific to each fixed- and rotary-wing asset, the Design and Demonstrate phases set the baseline for airframe wear and fatigue. The Design phase assumes a "severe" service usage, or a reasonable maximization of potential airframe stress for any particular flight. This assumption creates conservative ceilings for airframe and aircraft component fatigue limits, thereby minimizing structural failure due to fatigue. This approach creates a usage baseline that reduces vulnerability to variability in service usage. Next, the Demonstrate phase incorporates the assumptions of the Design phase by performing a spectrum, or full-scale, "severe" usage, fatigue test on the airframe, landing gear, and other dynamic components. This test pinpoints critical areas on the aircraft for gross failures and sets the criteria for destructive or non-destructive inspection requirements. When combined, these results become the Fatigue Life Standard (FLS) for that particular airframe.

The Track phase is the most critical of the SLMP process. Also known as the Structural Appraisal of Fatigue Effects (SAFE) program, tracking allows for continuous updating of the amount of fatigue life that each aircraft has used. Managed by NAVAIR 4.3.3.4 Aircraft Structural Life Surveillance Branch, Boeing's SAFE software tracks each F/A-18 through the collection of usage, load, and configuration data while focusing on maximum airframe service without exceeding service life limits (Claus, 2009). This data is continuously analyzed to compare the accrued service usage as measured by FLE against the maximum allowable life of the FLS. This data is susceptible to error; accuracy is completely dependent on NAVAIR's ability to reproduce the load history of each aircraft.

2. Fatigue Life Expended

Fatigue, defined as the "…cracking or failure of the aircraft structure by repeated loading over time," is the primary concern in preventing aircraft loss due airframe and/or component failure (NAVAIR, 2007). FLE, however, is more than a raw measurement of accrued fatigue. Based on the FLS, it is the "…calculated amount of fatigue life used up at a critical location on an airframe or component" (Claus, 2009). FLE is not measured directly by the aircraft or sensors, but is calculated from recorded aircraft-mounted strain gages, total flight hours and landings, and component installation/removal history (accounting for parts moving between aircraft).

Based on a scale of 0.0 to 1.0, where 1.0 represents retirement of the airframe, FLE is a function of the original 6000 SFH for which the F-18 is designed. SFH, in turn, is derived from the full-scale testing of the airframe during production; it represents hours flown at "severe" usage. While it is common for a "gently-flown" aircraft to achieve AFH in excess of its SFH, the FLE allotment per airframe remains in compliance with the design rate in regards to SFH: 6000 SFH is equivalent to 100% airframe life and $\frac{1.0\text{ FLE}}{6000\text{ SFH}} = .167$ FLE per 1000 SFH (NAVAIR, 2007). This distribution of FLE over SFH does not represent how the actual damage number is determined. There are two techniques for calculating FLE on the airframe: the Boeing weight (NzW) method and the strain gage data collection method.

a. NzW Method

Boeing employs the NzW method for calculating FLE. Using monitored parameters of gravitational units (Nz) and aircraft weight coupled with known load ratios, the NzW method consists of four steps: cycle counting, notch stress and strain calculation, equivalent strain calculation, and damage calculation. The NzW FLE is more conservative than the strain gage FLE, so it is less desirable for use in managing airframe life. Details concerning FLE calculation based on the NzW method can be found in Boeing's F/A-18 A/B/C/D Methodology Report released September 2006

(Boeing, 2006). It is mentioned here because the NzW FLE is one of the parameters supplied in the data set that is used to predict the FLE used by NAVAIR to manage USN and Marine Corps F/A-18's.

b. Strain Gage Data Collection

There are seven sensor locations on the F/A-18 that house both primary and backup strain gages: the lower forward fuselage, the left hand (LH) wing root, the LH wing fold, both right hand (RH) and LH vertical tail attachment points, and on each of the RH and LH horizontal tails attachment points (Boeing, 2006). These sensors continuously measure deformations of their respective mounting surfaces during flight. Each sensor consists of multiple wire loops that run parallel to the direction in which the stress or deformation is expected. When a deformation occurs, the wires stretch and increase electrical resistance; this resistance is measured and transmitted as an analog signal to the Signal Data Computer (SDC). The SDC converts the signal from analog to digital and relays it to the Mission Computer (MC), which applies a dead band filter to the data. Because only local maxima and minima are required for analyses, the MC evaluates the difference between the two. If the difference is greater than 1 Nz, this "cycle" or peak/valley data pair is stored in the Data Storage Unit (DSU). If it is less than 1 Nz, the data is discarded and is not counted as a load event (Boeing, 2006).

The Marine Corps is primarily concerned with FLE of the wing root (WRFLE) because the wing roots take the majority of load placed on the aircraft during maneuvers. This is supported by Boeing's F-18 Methodology Report, which defines a critical reference condition (CRC) as the maximum allowable strain at each sensor location on the aircraft. The actual strain measurement is called the Reference Bending Moment (RBM). The WRFLE CRC occurs during a steady state pull-up maneuver at Mach 1.0, altitude of 15,000 ft., and normal acceleration of 7.5g's resulting in an RBM of 6,390,000 in-lbs. The wing root RBM is approximately 5,680,000 in-lbs greater than the next highest critical RBM, the RBM of the RH and LH horizontal tail attachment points. The WRFLE is the major contributor to the aircraft FLE.

3. Current Procedures

The FLE per flight is calculated by NAVAIR based on strain sensor data for that flight. These results are more accurate than the NzW equivalents when the sensor data for the corresponding flight are accurate. However, unlike the NzW method, they are subject to noise and bias from the strain sensor data. Because strain sensors are unmonitored systems, they are subject to failure and drift, either of which can introduce error into the strain data set for one or more flights. Uploaded by squadrons to SAFE daily, DSU data files for each aircraft are accumulated for approximately a month before they are screened for sensor anomalies. If an irregularity is found, NAVAIR relies upon the NzW method to produce the WRFLE rather than rely on WRFLE computed based on the sensor data. In these cases, the WRFLE is replaced by the less accurate NzW WRFLE. This approach yields a conservative FLE, so that aircraft appear to have accrued more FLE than they actually have. To compound this problem of managing aircraft using this approach, WRFLE are not relayed to the squadrons in a timely manner. Uncorrupted data sets are summarized and the WRFLE incurred by each aircraft over the previous month is reported back to the squadrons. The time it takes for squadrons to receive accurate WRFLE numbers back from NAVAIR is 5–7 weeks.

4. Australian and Canadian Procedures

The Australian F-18 fleet is managed by a program not unlike the SLMP used by the USN; there are, however, key differences that must be noted. The Australians use a software suite called ASLMP.Net (Airframe Service Life Monitoring Program) that is capable of generating monthly FLE reports, analyzing historical data to predict future usage rates, and assigning FLE rates to individual pilots, by training and readiness (T&R) codes, or by aircraft configuration (Jones, 2007). There is a much finer granularity in reporting and analysis available than in SLMP, an advantage brought about by the Mission Severity Monitoring Program 2 (MSMP2) software embedded in ASLMP.Net.

MSMP2 calculates FLE using two different methods. The first method is based on wing root strain and automatically evaluates for, and corrects, potential strain gage drift. The strain gage measurements are the primary values used for the actual damage

numbers for each aircraft because even with drift corrections applied, they are more accurate than the other calculation techniques. The second method, called VGH (Velocity, Gravity, and Height) is based on aircraft weight, velocity, altitude, and Nz (Jones, 2008). The VGH results are used to create reports for the Fatigue Planner portion of ASLMP.Net that predicts FLE based on preflight mission code, load configuration, and weight. All reports can be accessed through ASLMP.Net; managed at the squadron level, ASLMP.Net provides commanders with a valuable, real-time tool to manage their aircraft. Unlike the Australians with few squadrons, the USN and USMC have numerous ship and shore locations that would require ASLMP.Net. This prospect is too expensive given setup costs, training, and support personnel.

In addition to fiscal limitations, there are critical differences between MSMP2 and SAFE that make it unsuitable for the USN to field. Because Australian Hornets are not carrier-based aircraft, MSMP2 focuses on WRFLE and disregards shipboard procedures like catapult or trap. More importantly, the damage models used to calculate WRFLE differ due to separate spectra tests. Rather than subscribe to the spectra tests conducted for the Navy by McDonnell Douglas during the Hornet's system development phase, the Australians conducted their own tests that better represented the manner in which they fly the aircraft. This resulted in completely different damage models, aircraft FLE limits, and airframe life limits. MSMP2 is tailored to these limits and adapting MSMP2 to USN flight styles is not viable.

Like the Australian Air Force, the Canadians concluded that the McDonnell Douglas spectra tests were not tailored to their flight styles. This led them to conduct their own tests in the early 1990s (Canadian Defense Staff, 2001). Without access to proprietary software, they had to tailor their SAFE software to match the results attained from their tests. With their modified SAFE, the Canadians use the SLMP; they lack a real-time tool for implementing their program and face data latency issues like those of the USN.

B. OBJECTIVE

Data latency in WRFLE reporting from NAVAIR is the motivating factor for this thesis. Because the reporting process typically takes five to seven weeks, squadrons are susceptible to flying high-FLE "red" aircraft in high-FLE missions when lower-FLE aircraft could have been used. PMA-265, the Marine Corps F/A-18 A-D air vehicle team from Patuxent River, Maryland, is working with Boeing on a software solution to this problem. This Boeing WRFLE tool will use monitored flight metrics and the NzW method to predict strain gage WRFLE; this alleviates the potential for drift or failure.

The objective of this thesis is to create and statistically validate eleven models that will be coded into Boeing's real-time WRFLE tool as the baseline for predicting the NAVAIR WRFLE response.

C. SCOPE AND LIMITATIONS

1. Scope

The Marine Corps F-18 T&R manual states that there are six Skill, eight Mission, and four Core Plus Skill codes that can be logged for any given flight (NAVMC 3500.50, 2008). Because Navy flight codes differ from those in the Marine Corps T&R, it is necessary to group flights of similar mission scope. Through this procedure, 11 of the 18 Marine codes are represented. It is from these mission family codes (MFC) that the regression models are formed and are therefore applicable to both services. The 11 models are developed for the following MFC:

- Air-to-Air (AA)
- Anti-Air Warfare (AAW)
- Air-to-Surface (AS)
- Close Air Support (CAS)
- Familiarization Flight (FAM)
- Functional Check Flight (FCF)
- Field Carrier Landing Practice (FCLP)
- Ferry/Escort Flight (FERRY)

- Low Altitude Tactics (LAT)
- Night Systems (NS)
- Strike (STK)

2. Limitations

The results of this thesis are limited to F/A-18 A-D Type Model Series (TMS). Because the Marine Corps uses only TMS A-D aircraft, Super Hornet (TMS E-F) are not evaluated. Further, NAVAIR's data is limited to TMS A-D. Thus, the predictive models developed in this thesis are applicable only to USN and USMC F-18 A-D aircraft.

Out of the 18 mission, skill, and core skill codes described in the USMC T&R, only 11 of the codes are modeled. In the case of the other seven codes, the data used in this thesis contains too few records of these codes to make a valid prediction. Therefore, some core skill and skill codes are not modeled.

3. Assumptions

For prediction, we assume common mission flight profiles for the USN and USMC. While USN and USMC flight codes differ, the manner in which the aircraft is flown during missions common to both services is similar. Defining umbrella MFC is essential in grouping flights common to both services. This grouping is supported by the joint mission of Operation Iraqi Freedom in which USN and USMC Hornets were called upon to perform similar missions in support of the ground troops. The missions that included catapult and trap, and that are most applicable to the USN, are not included in the 11 mission models given the focus on WRFLE in this thesis.

D. THESIS ORGANIZATION

Discussion of the data used to develop the 11 models, including variables, assumptions, and methodology, appears in Chapter II. Chapter III includes detailed analysis for three MFC. Chapter IV gives conclusions and recommendations. Definitions of all mission type codes (MTC) can be found in Appendix A. Appendix B contains definitions and omission justification for all unused variables. Explanations of all models not discussed in Chapter III can be found in Appendix C.

II. DATA AND METHODOLOGY

A. DATA SET

The data set supplied by NAVAIR consists of 2748 records from a FLE study, conducted between 2007 and 2008. The data includes records from both USN and USMC fleet and training squadrons. All study aircraft are TMS A-D and are paired with more than 80 different mission type (MTC) and mission family codes (see Appendix A). These codes are condensed down to the 11 mission family codes that the models are based upon.

Each row in the data set represents one flight and is hand-paired by NAVAIR. "Hand-paired" means that each flight record consists of the original DSU data file matched with the resulting NAVAIR WRFLE and corresponding Boeing NzW WRFLE. Each record contains numeric and factor variables, some of which are not useful for analysis. Of the 33 columns that make up the data in each record, only 10 are practical to use in creating the models, grouped by MFC, as will be discussed in the next section. Explanations of columns not used can be found in Appendix B. It is important to note that errors have been found in the data due to the hand-pairing. These errors lead to assumptions about the data that are discussed later as well.

B. VARIABLES

1. Type

The categorical variable "Type" represents the TMS of the aircraft and has levels "A", "B", "C", or "D". This is an important factor due to differing weights, number of aircrew, and potential configurations among the TMS. Also, the records in the data set involve all four TMS across same type mission codes, so the distinction among TMS is necessary. "TypeA" is the baseline level in the models containing all four TMS with coefficients assigned to "TypeB", "TypeC', and "TypeD".

2. Centerline (CL)

"CL" is a binary variable that describes whether or not a centerline fuel tank is used at store station five on a particular flight. Store station five is located on the belly of the Hornet and a full 330 gallon CL tank adds approximately 2400 pounds to the aircraft load. This additional weight influences the strain placed on the wing roots during both positive and negative Nz maneuvers.

3. Left Wing Ordinance and Left Store Station (Left)

Left Wing Ordinance (LWO) refers to the type of ordinance mounted on the left side of the Hornet during the flight. It includes various types of inert or active bombs, active or captive missiles, and/or Forward Looking Infrared (FLIR) pods. Left Store Station (LSS) refers to the store stations used for munitions carriage and includes stations one, two, three, and four. These cells are critical as they describe added wing load and directly affect the WRFLE. The "Left" variable is a binary indicator variable that results from the combination of LWO and LSS. A "1" represents a flight record in which both LSS and LWO cells contain entries other than "None"; a "0" results otherwise.

4. Right Wing Ordinance and Right Store Station (Right)

See Left Wing Ordinance and Left Store Station.

5. Weight Off Wheels Time (rDHCnt)

The numeric rDHCnt variable, measured by the aircraft, is the total flight weight off wheels time and is reported by the DSU. While the data set also contains a numeric Flight Hour (FH) column, rDHCnt is more accurate. The FH entries result from pilot input on the Naval Aviation Flight Record (NAVFLIR) form and are subject to variability and inaccuracy that rDHCnt is not. Tracking the rDHCnt is significant for WRFLE prediction, as it helps smooth the variance between longer sorties that could contain multiple mission codes not listed in the record and shorter, more aggressive single-code flights.

6. Wing Root Triggers (WRTrigCnt)

The numeric WRTrigCnt variable is the total number of wing root trigger events that fall outside the dead band for each flight (see Strain Gage Data Collection). This variable is also critical to WRFLE prediction in that it creates a measure for the aggressiveness of the mission and aircrew during a given flight.

7. Maximum Nz Normalized to 7.5 (rNzMax)

The numeric rNzMax variable represents the maximum Nz event of the flight. "Normalized" in this case means that max Nz event is divided by the maximum allowable Nz of 7.5 (Naval Air Systems Command, 2008). With 0.0 representing 2 Nz or less, the range should be 0.0 – 1.0. There are instances in the data set, however, where rNzMax exceeds 1.0. Because it is possible to achieve more than 7.5 Nz, and there is a buffer region up to 8.1 Nz before a maintenance action is required, rNzMax over 1.0 are allowable for modeling purposes.

8. Minimum Nz Normalized to 7.5 (rNzMin)

The numeric rNzMin variable represents the minimum Nz event of the flight. Also divided by 7.5, the range of this column spans $-0.27 - 0.00$. Negative rNzMin are both possible and allowable due to negative Nz pushovers and/or dives.

9. NAVAIR Reported WRFLE (dWR)

As part of the hand-pairing of the data set, the numeric dWR variable is the calculated and verified strain gage WRFLE reported by NAVAIR for each record in the data set. This variable is set as the response for all models in this thesis.

10. Boeing NzW Method Number (dWRFill)

The numeric dWRFill variable is the calculated NzW number resulting from parameters recorded during and reported after each flight by the DSU (see NzW Method).

While the NzW result can be calculated immediately after each flight, it is less accurate than dWR. In the models, dWRFill is the most important predictor for dWR.

C. ASSUMPTIONS

1. Store Station Interchangeability

Distinctions were made to separate RH and LH store stations as represented in the "Right" and "Left" variables. However, there were no distinctions made between individual store stations grouped on either side. For example, the four store stations on the left side (one, two, and three, four) are all considered to be the same for wing loading purposes – utilization of one or more of the four stations results in a single instance of "Left." This is the most detailed manner in which the LSS and LWO variables can be modeled given the limitation of the records in the data set.

2. Type Conversion

In many MFC subsets, there are too few records of a specific Type to assign weights to, or provide useful interactions between, A, B, C, and D. Specifically, subsets exist in which there are four or fewer records of Type A and/or four or fewer records of Type B. Therefore, assumptions are made to group the Type A with Type C and/or Type B with Type D records. In these cases, Type A is converted to Type C for grouping – both are single seat aircraft and weights, munitions loads, and wing root loadings are similar. Type B is converted to Type D using the same rationale with both B and D being dual-seat aircraft.

3. Missing Data or Ambiguous Records

As noted before, there are several columns in the data set that contain values from the NAVFLIR completed by the aircrew after each flight. These columns are subject to individual interpretation and error that the metrics reported by the DSU are not. Therefore, many records are either incomplete or list erroneous or ambiguous mission type codes. These records are discarded for this study and are listed below:

- Four records lacking MTC's or mission family codes
- Two record with MTC "Spare" - Ambiguity
- Three records with MTC's "Alert15" and "Alert 30" - Ambiguity
- Two MTC "Not Coded" - Ambiguity
- One record with MTC 436 – Not defined in USMC T&R
- Two records with MTC "TSITPITTS" – Not defined by USN
- One record with MTC "NIP" – Not defined by USN

A total of 15 records are discarded for these reasons.

4. Mission Codes

The data set contains numerous mission type and mission family codes for which there are 25 or fewer records. The data set also contains mission type codes that are only applicable to the USN (i.e., FBFM). These codes have up to 409 records but cannot be used due to lack of interchangeability with Marine Corps T&R codes. Consequently, both USN-specific and mission type codes with small samples are grouped with other mission codes into 11 larger umbrella mission family codes that are applicable to the Marine Corps. Table 1 lists the grouping assignments made to USN and USMC mission codes with 25 or fewer records. Further explanation of MTC's can be found in Appendix A.

Table 1. Mission code assumptions and total MFC records

Small Sample & USN MTC's	MFC	Number of Records
251, 252, 613, ACT, ADEX, FBFM, DCA, FOCF, REDAIR, SXN MAN, SEM, SF 10-11	AA	738
471, 497, 4VXDCA, FSRA, FFWT, FWT, SWEEP	AAW	326
236-239, 242, 253, 254, LAHD, SF 1-4, SF 6-7	AS	95
291, 310, 312, AR, DAS, FAC(A), SCAR	CAS	196
201, 210, FAWI, CURRENCY, FFRM, ROLL&GO, SUPT, WU	FAM	244
PMCF, PRO	FCF	29
FCQL, FLYOFF, FLYON	FCLP	180

AIRNAV, CHASE, FIFR	FERRY	80
282, 513, DEMO	LAT	62
251-254, FNAT, FNVG	NS	32
AI, AIC, SES	STK	268
Total records		**2250**

5. Hand-Pairing Record Errors

Errors in the pairing of records occur within the data set; they are identified by disparity between rDHCnt and FH. According to AIR-4.3.3.4, the following two conditions are permissible:

- rDHCnt can be up to 10% greater than the logged FH
- FH can exceed rDHCnt by up to 30%

These two limitations create upper and lower boundaries on the gap between rDHCnt and FH. Applying filters to the data set, 83 records are found where rDHCnt exceeds FH by more than 10% and 325 records contain FH's that surpass rDHCnt by more than 30%. These 408 total records are considered pairing errors and are discarded from the data set to ensure modeling integrity.

Using an approach agreed to by NAVAIR, records with aggressive mission family codes and abnormally low WRTrigCnt are also considered errors and are discarded. For example, AA is considered a high Nz loading mission so WRTrigCnt's of zero to 10 are impractical. These records are discarded while records above 10 WRTrigCnt are kept. Table 2 lists the mission family codes and the number or records discarded due to impractical WRTrigCnt's after the rDHCnt/FH filter is applied.

Table 2. Records deleted due to WRTrigCnt and rDHCnt/FH abnormalities

Mission Family	Abnormal WRTrigCnt Range	WRTrigCnt Deletions	rDHCnt & FH Deletions	Total Records Deleted
AA	0-10	27	117	144
AAW	0-2	7	30	37
AS	0-5	5	7	12
CAS	0-5	6	26	32
FAM	0-3	29	32	61
FCF	0-5	0	15	15
FCLP	None	N/A	81	81
FERRY	40 or more	5	52	57
LAT	0-10	4	17	21
NS	0-5	0	4	4
STK	0-10	19	27	46

D. METHODOLOGY

The models within this thesis are fit using linear regression. For each of the 11 mission codes, the dWR response is predicted by the factors of, and interactions between, dWRFill, Type, CL, Left, Right, rDHCnt, WRTrigCnt, rNzMax, and rNZMin.

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III. ANALYSIS

A. INITIAL OBSERVATIONS

An initial model of dWR as a linear function of the 10 variables given in Chapter II is fit to the entire data set of 2250 records. Exploration of the fit begins with plotting the residuals versus the fitted values for this model, shown in Figure 1. Inspection shows heteroscedasticity among the residuals with an increasing trend. The response versus fitted values plot in Figure 1 also shows increasing variance. In order to address this issue, a transformation of the response is necessary.

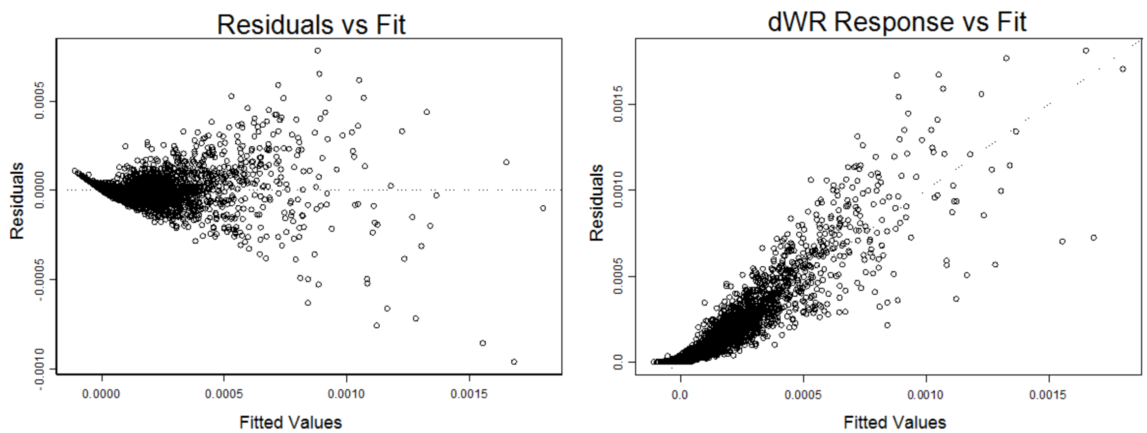

Figure 1. Initial residuals versus fitted values and response versus fitted values

Numerous power transformations of the response are explored, including $\sqrt{y}$ and $\ln(y)$, where y is the response variable. The transformation that works best to stabilize the variance is found to be $y^{1/4}$. As shown in Figure 2, the residuals from a linear model utilizing $y^{1/4}$ and fit to all the data exhibit a more homoscedastic variance and the response versus fit plot is closer to linear. It is noted that the graphs still exhibit some properties of increasing variance. Also, both plots contain a linear feature near the point (0,0); this feature is associated with a set of flights for which the response variable dWR is exactly zero. These attributes are not present in the models built using the 11 MFC subsets. This determination, coupled with the Normal quantile-quantile plot of the

residuals (Figure 3), suggests that the assumption of normal errors and constant variance is plausible and parametric tests are feasible for analyzing this data set.

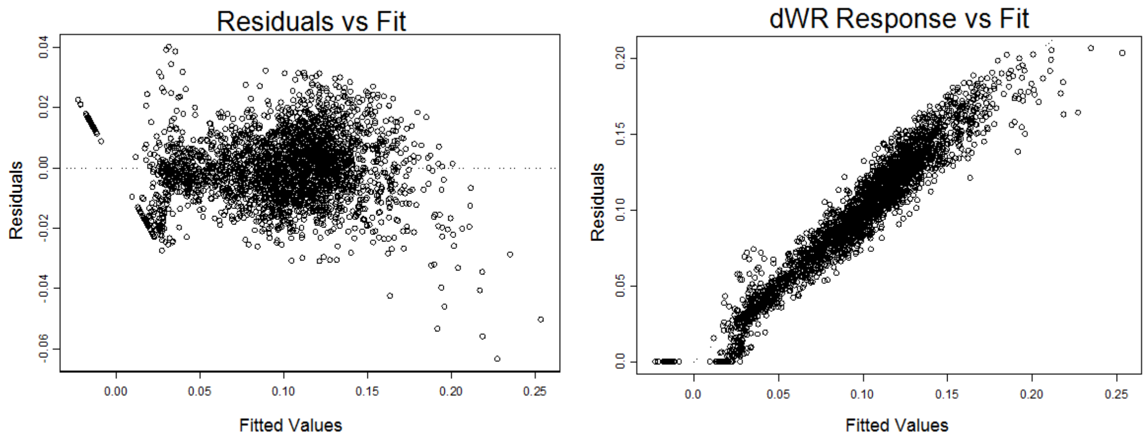

Figure 2. Residuals versus fit and response versus fit plots based on the linear regression fit model with transformed response

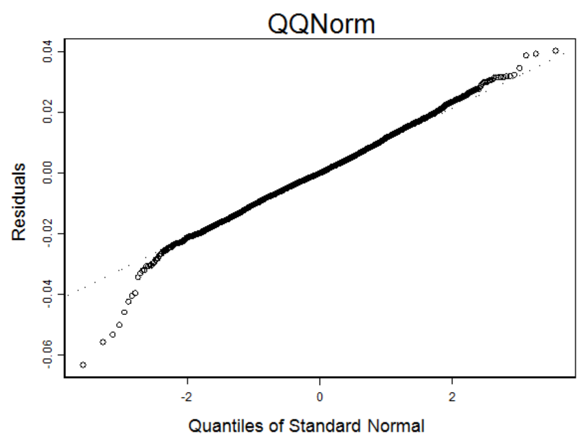

Figure 3. Normal quantile-quantile plot of residuals based on the linear regression model with transformed response

Given the approximately linear relationship between dWR and dWRFill, it is appropriate to transform dWRFill to the quarter power as well. As shown in Figure 4, in which dWR, dWRFill and transformed dWR, dWRFill are plotted against their corresponding record number, the transformation more uniformly spreads out the observations with dWR and dWRFill massed close to zero. The transformation of dWRFill is therefore used in the analysis of all MFC data subsets.

The analysis of the AA, FAM, and FCF MFC's are included in this chapter. These MFC's are chosen based on the record size of each subset. The AA MFC contains

738 records and represents the largest sample size in the data set. The FAM MFC contains 244 records and represents a mid-range sample size in the data set. The FCF MFC contains 29 records and represents the smallest sample size in the data set.

In this chapter, models are stated without coefficients. Coefficients for all MFC and model fits for the remaining eight MFC not contained in this chapter can be found in Appendix C. Also included in Appendix C is an analysis of the entire data set without respect to MFC.

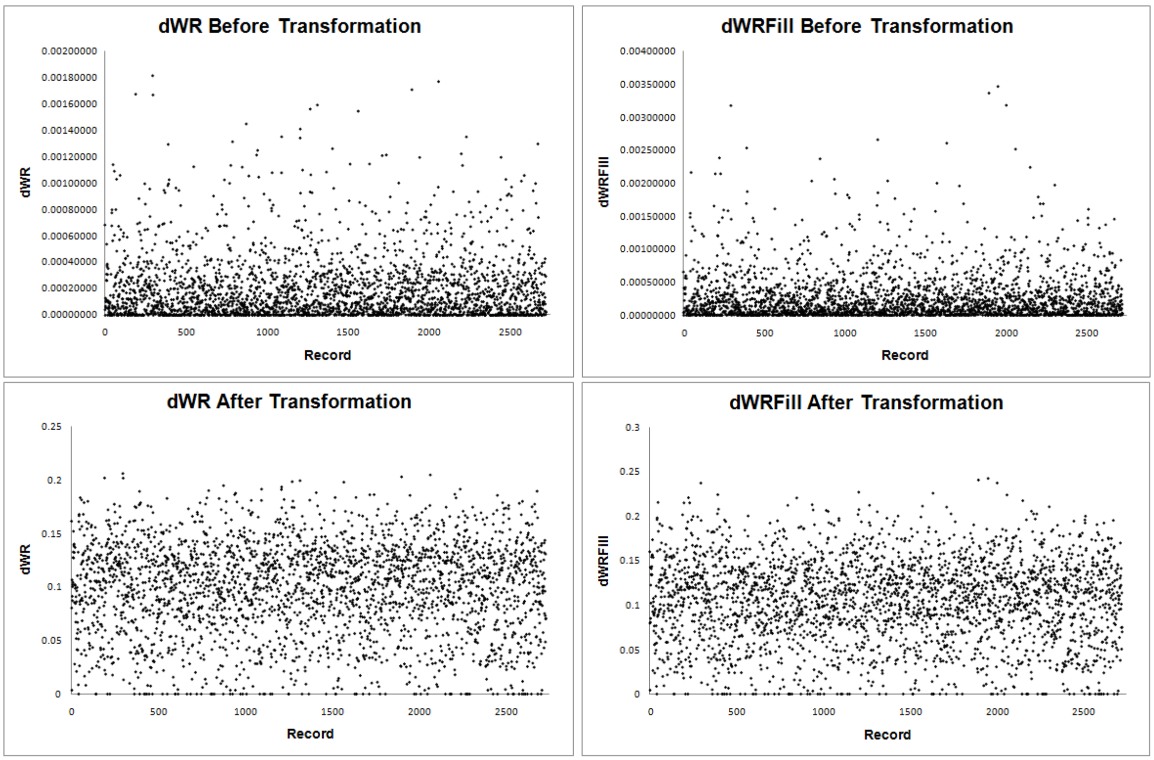

Figure 4. dWR and dWRFill vs. record number before and after power transformation

B. AA MFC SUBSET

The first and largest MFC subset to be evaluated is AA. This MFC contains 738 records. In this case, 152 records contain entries in LeftStoreStation and LeftWingOrdinance and 62 records contain entries in RightStoreStation and RightWingOrdinance. These numbers are large enough, so both variables Left and Right are used in the initial model fit.

The categorical variable Type is evaluated next, to ensure that enough A’s, B’s, C’s, and D’s are present to properly weight each level. Table 3 shows the results of tabulating the Type variable for the AA MFC.

A	B	C	D	**Total**
247	47	363	81	**738**

Table 3. Type variable representation in the AA MFC subset

These results suggest that all four levels Type A, Type B, Type C, and Type D may be included in the model and that grouping is unnecessary.

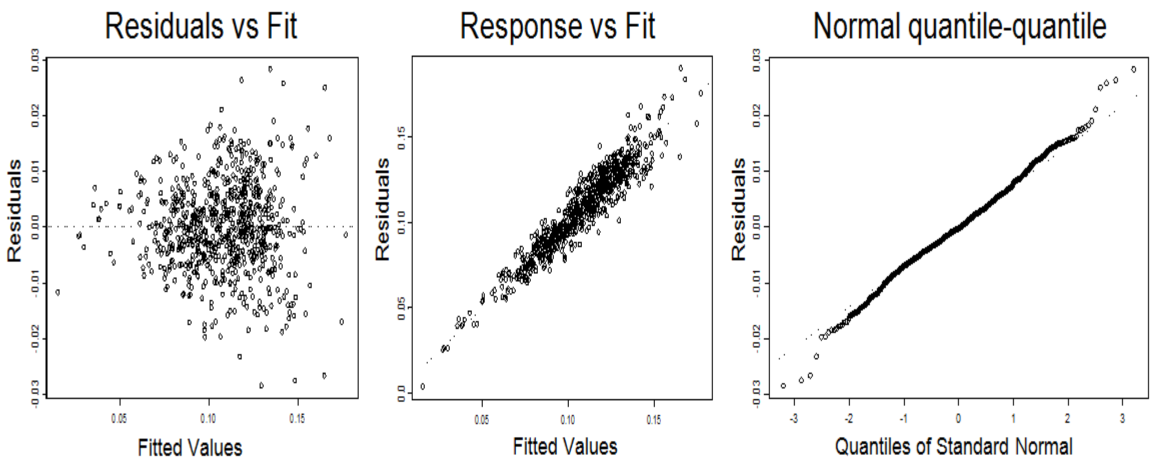

Figure 5. AA model plots without interaction terms

Using the transformation of dWR and dWRFill, the initial model is $\text{dWR}^{0.25}$ ~ Type + CL + rDHCnt + WRTrigCnt + rNzMax + rNzMin + $\text{dWRFill}^{0.25}$ + Left + Right. Within this thesis, models will be presented in this form. The term to the left of the “~” is the response, “~” implies “is modeled by”, and the terms to the right of the “~” are the regressors. The model specification above is additive in the response. Interaction terms are specified by “:” between variable names. As shown in Figure 5, the residuals exhibit homoscedastic properties and the response versus the fitted values plot shows a linear relationship. The Normal quantile-quantile plot exhibits a normality with deviations of less than 0.01 at the ends. With a residual standard error (RSE) of 0.00799, a maximum Cook’s Distance of 0.07 (indicating that no one observation is very influential), and an R^2 adjusted of 0.8992, this model fits sufficiently well to use for a stepwise selection process using two-way interactions.

The stepwise selection process used for all models is the stepAIC function that resides within the MASS library of the S-Plus software package (Insightful Corp., 2007). The stepAIC function is a function that uses Akaike Information Criterion (AIC) to compare models as parameters are passed in and out until the model with the smallest error is found. See Akaike (1974) for more detailed information on AIC. More information on the stepAIC function can be found in the MASS library of SPlus (Venables and Ripley, 2002).

Using stepAIC and all two-way interactions, the model becomes more complicated, but the maximum Cooks Distance decreases to 0.04, the R^2 adjusted increases to 0.9107, and the RSE decreases to 0.00761. Shown in Figure 6, the plots retain the same properties as the original model which leads to exploring further validation.

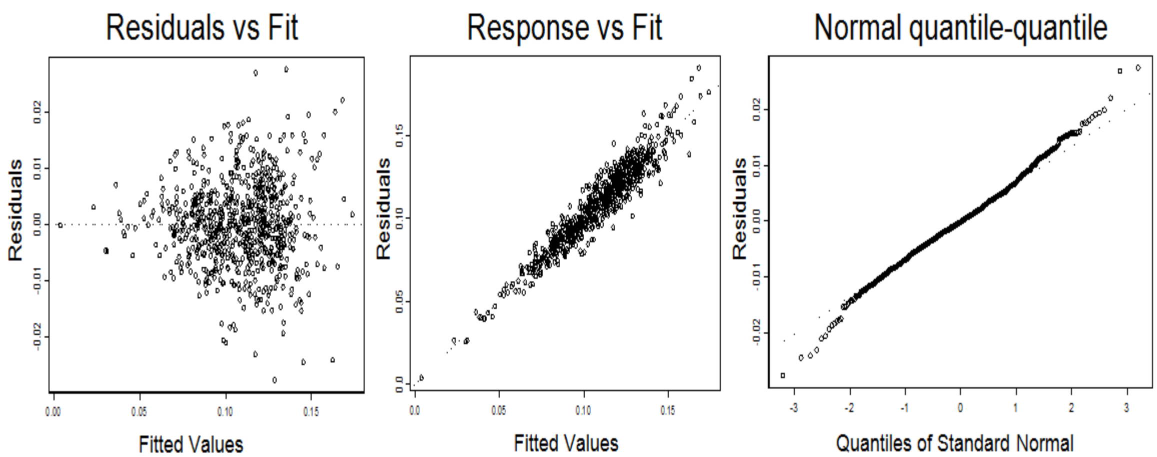

Figure 6. AA model with interaction terms

Under the usual assumptions, a partial F-test can be used to assess the significance of each term in the model. For all models in this thesis, a Type III Sums of Squares (SS) Analysis of Variance (ANOVA) table is used to construct the F-statistics. Type III SS uses an unweighted means analysis to test for significance (Montgomery Douglas C., Elizabeth A. Peck, and G. Geoffrey Vining, 2006). Each term in the model contributes to a decrease in AIC; Table 4 shows the terms and F-statistics associated with each one.

Table 4. ANOVA table for AA with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	3	2.19e-4	7.29e-5	1.26	0.288
CL	1	4.02e-4	4.02e-4	6.94	0.00861
rDHCnt	1	2.09e-4	2.09e-4	3.6	0.0581
WRTrigCnt	1	0.00241	0.00241	41.6	0.0
rNzMax	1	0.004	0.004	69.0	0.0
rNzMin	1	2.16e-5	2.16e-5	0.373	0.542
$dWRFill^{0.25}$	1	4.44e-4	4.44e-4	7.66	0.0058
Left	1	4.32e-4	4.32e-4	7.46	0.00646
Right	1	1.5e-4	1.5e-4	2.59	0.108
Type: $dWRFill^{0.25}$	3	0.0013	4.34e-4	7.49	6.11e-5
WRTrigCnt:rNzMin	1	5.75e-4	5.75e-4	9.92	0.00171
Type:rNzMax	3	5.16e-4	1.72e-4	2.97	0.0313
rNzMax:Left	1	2.79e-4	2.79e-4	4.82	0.0284
Type:CL	3	5.09e-4	1.7e-4	2.93	0.0329
WRTrigCnt:$dWRFill^{0.25}$	1	2.09e-4	2.09e-4	3.61	0.058
rDHCnt:rNzMax	1	9.32e-4	9.32e-4	16.1	6.7e-5
rDHCnt:$dWRFill^{0.25}$	1	0.00102	0.00102	17.5	3.17e-5
rNzMin:$dWRFill^{0.25}$	1	4.04e-4	4.04e-4	6.97	0.00847
rDHCnt:WRTrigCnt	1	2.2e-4	2.2e-4	3.8	0.0517
CL:rDHCnt	1	5.1e-4	5.1e-4	8.8	0.00311
rDHCnt:Left	1	3.42e-4	3.42e-4	5.9	0.0154
Residuals	708	0.041	5.79e-5	NA	NA

The last step in the analysis process is the cross-validation of the selected model. Cross validation is performed by partitioning the data into 10 separate subsets and fitting the model, with each subset left out in turn. The residual sums of squares errors are collected and averaged. A model that exhibits "goodness of fit" will have a cross-validated RSE that closely matches the RSE of the original model.

Cross-validation is performed 30 times and the mean of the 30 average RSE's is 0.00781. With the difference between the RSE and cross-validation mean being 0.00019, the model is validated and is appropriately fit. The final form of the AA model is $dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Left + Right + Type{:}dWRFill^{0.25} + WRTrigCnt{:}rNzMin + Type{:}rNzMax + rNzMax{:}Left + Type{:}CL + WRTrigCnt{:}dWRFill^{0.25} + rDHCnt{:}rNzMax + rDHCnt{:}dWRFill^{0.25} + rNzMin{:}dWRFill^{0.25} + rDHCnt{:}WRTrigCnt + CL{:}rDHCnt + rDHCnt{:}Left$.

C. FAM MFC SUBSET

The FAM MFC subset is the next to be evaluated. It contains 244 records. As with the AA subset, the decision to use "Left" and/or "Right" must be made prior to creating the model. This subset includes 35 records in which LeftStoreStation and LeftWingOrdinance contain entries other than "None" while only one record contains entries for RightStoreStation and RightWingOrdinance. Therefore, only the variable "Left" is included in the initial model.

The categorical variable "Type" is evaluated next. TMS A and B are each represented by only four records, so grouping is required. Therefore, only TMS C, with 121 records, and D, with 123 records, are included in the model.

Applying the transformations of dWR and dWRFill, the preliminary model is $dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Left$.

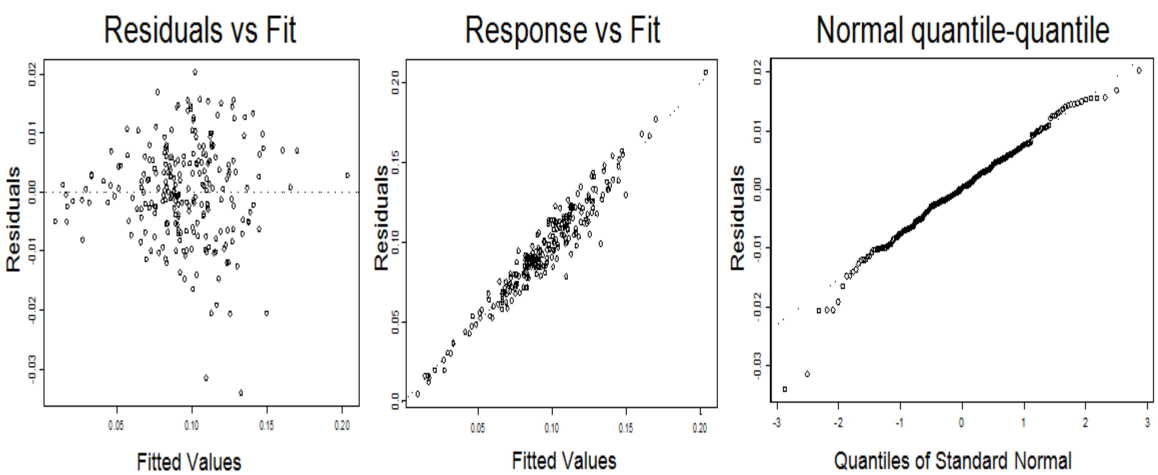

Figure 7. FAM model plots without interaction terms

As shown in Figure 7, the initial plot of the residuals versus the fitted values exhibits homoscedastic properties while the response versus fitted values plot confirms a linear relationship. The Normal quantile-quantile plot illustrates normality with maximum deviations at the tails of 0.01 which are acceptable given the model's RSE of 0.0083. The maximum Cook's Distance of any record in the model is 0.16, which

implies that there are no overly influential records. With an R^2 adjusted of 0.9273, the model is ready for the step-wise selection process using two-way interactions.

Applying the stepAIC function, five interaction terms are added to the previous model (see Figure 8). The residuals versus fitted values plot shows better homoscedasticity than the initial model plot exhibits, while the response versus fitted values plot illustrates a more compact linear relationship. The Normal quantile-quantile plot again suggests the normal assumption is valid.

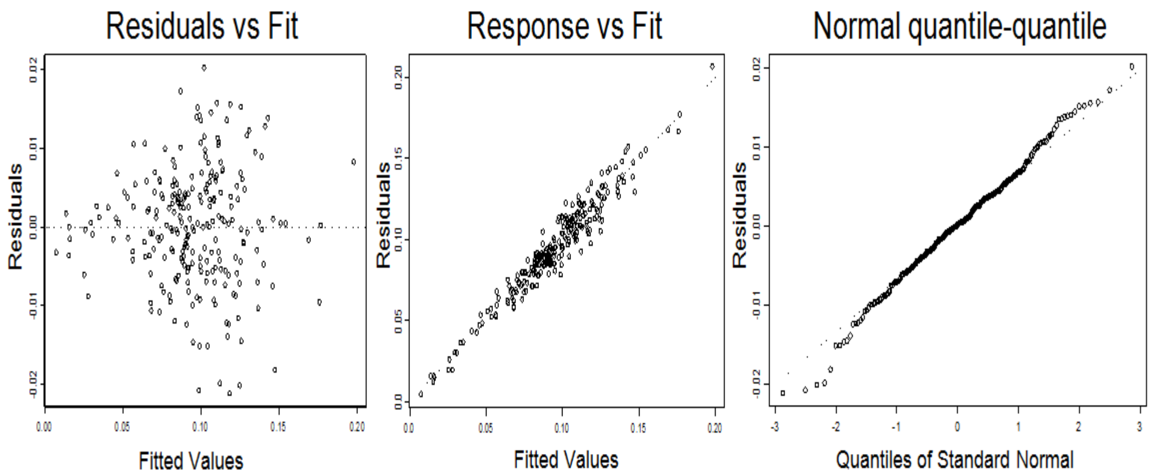

Figure 8. FAM model plots with interaction terms

With a maximum Cook's Distance of 0.24, it is determined that there is no overly influential record in the model.

To validate the significance of the interaction terms in the model, partial F-tests are performed. As shown in Table 6, the corresponding ANOVA table suggests that the rDHCnt:rNzMin interaction term may not be significant to the model. However, when this interaction term is taken out and the model is recalculated, the R^2 adjusted decreases by more than one percent. The decision to keep all interactions is made in order to explain as much of the variability in the model as possible. The resulting model has an RSE of 0.00759 and an R^2 adjusted of 0.9404.

Table 5. ANOVA table for FAM with interaction terms

Terms	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Type	1	1.73e-4	1.73e-4	3.0	0.0846
rDHCnt	1	1.86e-4	1.86e-4	3.23	0.0736
WRTrigCnt	1	1.34e-5	1.34e-5	0.233	0.63
rNzMax	1	0.00194	0.00194	33.7	0.0
rNzMin	1	2.3e-4	2.3e-4	3.99	0.047
$dWRFill^{0.25}$	1	0.00973	0.00973	169.0	0.0
Right	1	1.86e-4	1.86e-4	3.22	0.074
$rNzMin:dWRFill^{0.25}$	1	0.00111	0.00111	19.2	1.8e-5
$WRTrigCnt:dWRFill^{0.25}$	1	4.27e-4	4.27e-4	7.41	0.00699
WRTrigCnt:rNzMin	1	2.82e-4	2.82e-4	4.88	0.0281
$Type:dWRFill^{0.25}$	1	2.34e-4	2.34e-4	4.05	0.0453
rDHCnt:rNzMin	1	1.17e-4	1.17e-4	2.03	0.156
Residuals	230	0.0133	5.77e-5	NA	NA

The last step in the process is to cross-validate the FAM model. The mean average RSE across 30 cross-validations is 0.00837. This suggests the model exhibits goodness of fit and is valid. The final form of the FAM model is $dWR^{0.25} \sim Type + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Right + rNzMin{:}dWRFill^{0.25} + WRTrigCnt{:}dWRFill^{0.25} + WRTrigCnt{:}rNzMin + Type{:}dWRFill^{0.25} + rDHCnt{:}rNzMin$.

D. FCF MFC SUBSET

With 29 records, the smallest subset within the data set is the Functional Check Flight MFC. This subset is treated in the same manner as the previous two subsets, with the usage of variables “Left” and “Right” being evaluated first. Because no training or live munitions are carried on an FCF, neither “Left” nor “Right” is included in the model.

In this subset, there are two records of Type A with the rest being Type C or D. Due to the small number of TMS A records, Type A’s are converted to Type C’s. This results in 21 occurrences of Type C and eight occurrences of Type D.

The initial linear model, after applying the transformations to dWR and dWRFill is $dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFil^{0.25}$.

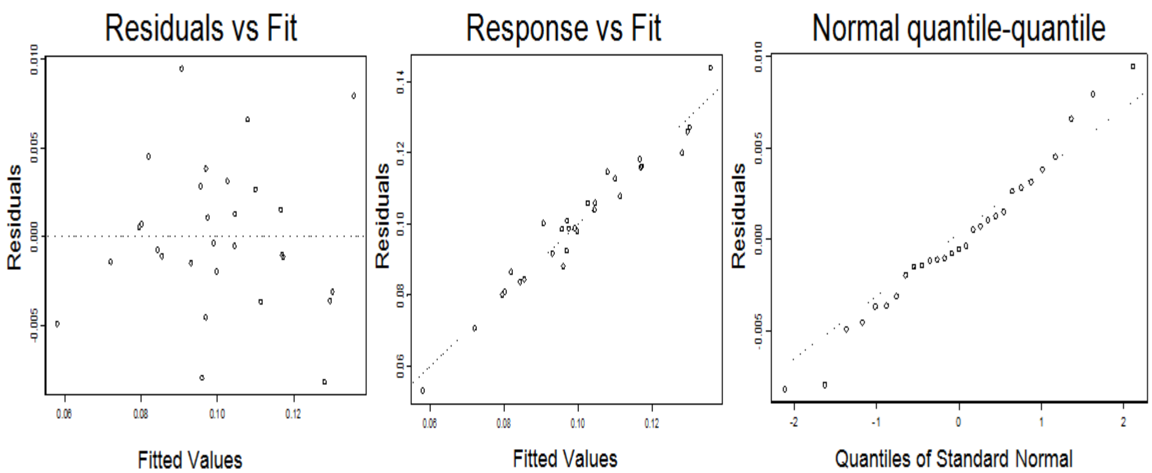

Figure 9. FCF model plots without interaction terms

The primary plots indicate a good fit givem the number of observations. With a maximum Cook's Distance of 0.5, RSE of 0.00481, and an R^2 adjusted of 0.9508, the model is ready for the step-wise selection process.

The model resulting from the stepAIC selection includes two interaction terms and does not include weight-off-wheels time. As shown in Figure 10, the plots are better than those of the initial model in regards to homoscedasticity, the prediction of the response, and normalcy. The RSE of the model is 0.00394 with an R^2 adjusted of 0.9685.

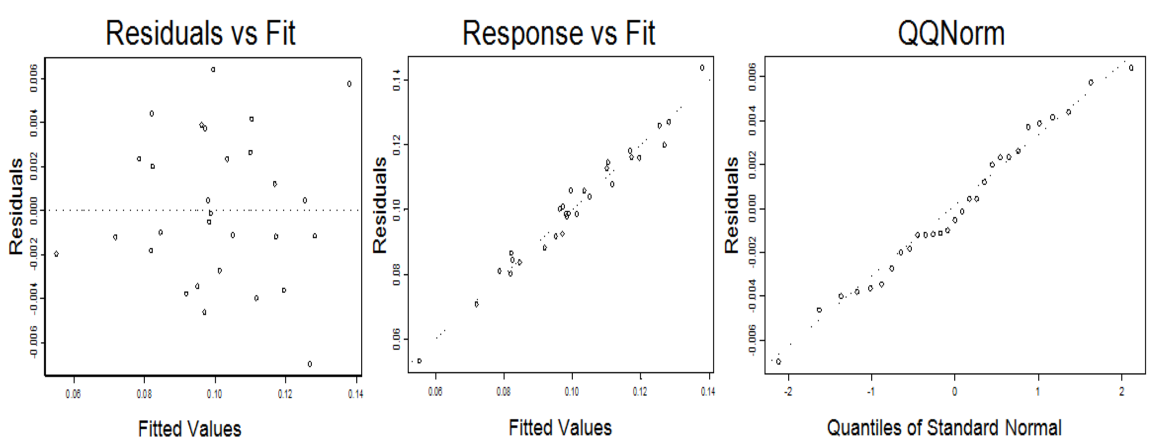

Figure 10. FCF model plots with interaction terms

Evaluating the model using ANOVA and Type III SS, it is found that all terms in the model are significant and should be included. This leads to the final step of cross-validation.

Terms	**Df**	**SS**	**Mean Sq**	**F Value**	**Pr(F)**
Type	1	2.35e-4	2.35e-4	15.1	9.07e-4
CL	1	1.05e-4	1.05e-4	6.78	0.017
WRTrigCnt	1	7.59e-4	7.59e-4	48.9	0.0
rNzMax	1	7.56e-5	7.56e-5	4.87	0.0391
rNzMin	1	3.08e-4	3.08e-4	19.8	2.44e-4
$dWRFill^{0.25}$	1	0.00115	0.00115	74.2	0.0
$rNzMin{:}dWRFill^{0.25}$	1	1.72e-4	1.72e-4	11.1	0.00334
Type:WRTrigCnt	1	1.13e-4	1.13e-4	7.27	0.0139
Residuals	20	3.1e-4	1.55e-5	NA	NA

Table 6. ANOVA table for FCF with interaction terms

The mean average RSE of 30 cross-validations is 0.00565. With the difference between the latter and the interaction model's RSE of being 0.0017, the model of $dWR^{0.25} \sim Type + CL + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + rNzMin{:}dWRFill^{0.25} + Type{:}WRTrigCnt$ is sufficiently validated.

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IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Impact

The models created from this research have been accepted for utilization in Boeing's WRFLE prediction software. This software will be distributed to Marine fleet squadrons in August and will allow commanders to manage their aircraft with respect to WRFLE in real-time. Data accumulated from the prediction software and NAVAIR's FLE reports will be stored to understand the prediction variability over time. Besides understanding WRFLE as a function of MFC, the Marine Corps is also planning on using the data to profile aircrew with regards to WRFLE, as well as predict WRFLE accrued during deployment work-up and training programs like the Weapons Tactics Instructor Course.

2. Individual Models

Analysis shows that the data set can be partitioned into 11 different mission family code subsets. Each of these subsets is modeled to varying degrees of accuracy. The most variance is explained by the Field Carrier Landing Practice (FCLP) model fit with an R^2 adjusted of 0.9789 while the least variance is explained by the AA model fit with an R^2 adjusted of 0.9107. This is expected as the AA MFC is a general code that contains a grouping of small sample and USN-specific mission type codes. The large number of different MTC's contained in AA creates increased variability within AA. By comparison, the FCLP MFC includes few groupings; 174 of the 180 records have FCLP or FCQL (See Appendix A) MTC's within the original data set. An FCLP flight is the same flight as a Field Carrier Qualification Landings (FCQL) flight with regards to WRFLE; this explains the high R^2 adjusted and low RSE (0.0048).

The transformation to the quarter power for both the dWR response and the dWRFill factor variables is necessary in order to obtain homoscedasticity among the

residuals. This transformation is consistent throughout the data subsets and is effective in removing visible heteroscedastic trends among the residuals.

3. Entire Data Set

The creation of the 11 MFC subset models allows for the removal of erroneous records. These pairing errors are not visible within the non-partitioned data. Once these records are removed, analysis on the entire data is possible. Employing the same analysis processes used on the MFC subsets results in an extensive model that is successfully cross-validated. With an R^2 adjusted of 0.953, the entire data set model is potentially useful. There are, however, variance issues that are not exhibited in the subset models.

For example, the residual versus fitted values plot of the entire data set shows heteroscedastic properties even after the transformation of the dWR and dWRFill vvariables.

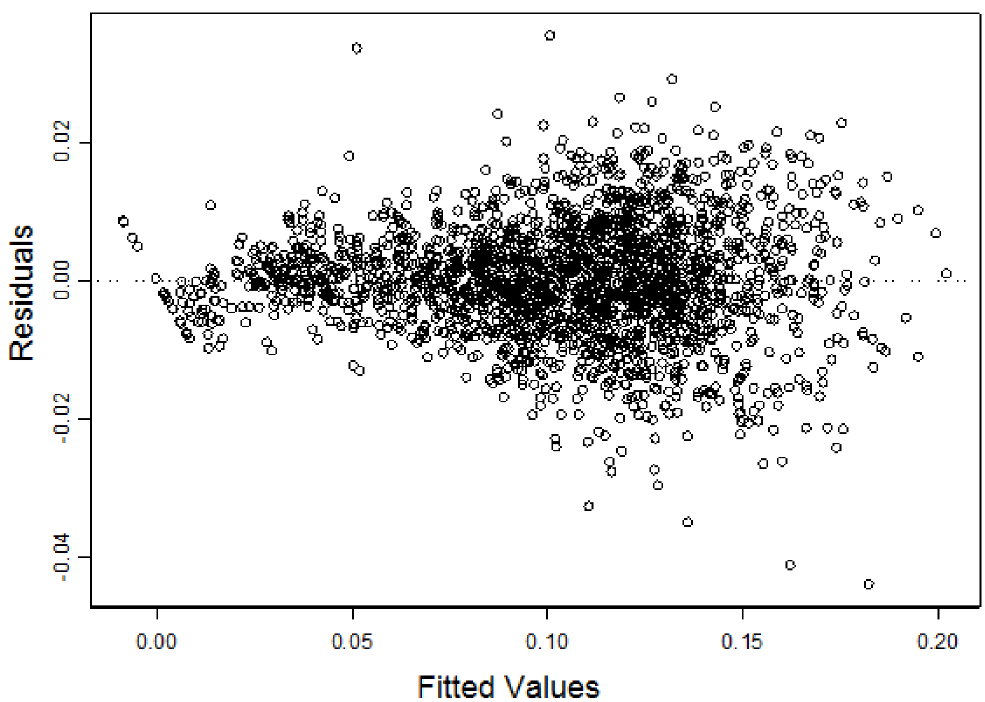

Figure 11. Entire data set residuals versus fitted values plot

This is a concern given the parametric tests used to validate the model. Also noted in Figure 11 is the linear feature around (0,0). This feature is brought about by 19 records

in which the dWR value equals zero, therefore violating the assumption of a continuous response variable. These records are valid, however, and fall within the Ferry MFC. It is concluded that this model may be useful for a point estimate, but the subset models are more accurate given the homoscedastic properties of the residuals within each subset.

B RECOMMENDATIONS

1. Data Collection

The wide variety of mission type codes within the data set supplied by NAVAIR results in grouping assumptions necessary to make all records relevant to the Marine Corps. It is recommended that PMA-265 maintain a data repository for the Marine F-18 fleet. Specifically, PMA-265 should maintain records of the variables used in this thesis by squadron, by flight. As data is aggregated, more accurate models can be created, specific to the mission, core skill, and core plus skill codes listed in the Marine Corps F-18 T&R Manual.

2. Further Analysis

This thesis provides a starting point from which the Marine Corps can build an accurate data library for predicting WRFLE. It is recommended that the analysis conducted in this thesis be conducted again once new, more accurate data is collected. This analysis would again require the pairing of the NAVAIR WRFLE number to a specific flight. This pairing is the source of the most identified errors within the data set and is critical because the accuracy of the analysis is completely dependent on accurate pairing. Better record-keeping of a data set dedicated to the prediction of NAVAIR FLE could alleviate this issue. Rather than going back years in an attempt to pair flights with FLE, the pairing would occur at the time of the FLE report and reduce the chance of errors.

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APPENDIX A

Table 7. Mission Type Code definitions and Number of Occurrences (NO)

MTC	DEFINITION	NO
201	FAM flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	5
236	AS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
237	AS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
238	AS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	4
239	AS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	4
242	AS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	2
251	NS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	2
252	NS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
253	NS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
254	NS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
260	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
261	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	2
262	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	4
263	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
265	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	5
268	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	10
269	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	4
270	AA flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
282	LAT flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
291	CAS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	2
302	CAS flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
310	AR flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	2
312	AR flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
321	SCAR flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
336	AAW flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
354	AI flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	2
387	FAC(A) flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
450	AAW flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
471	LFE flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	4
497	TAR flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
4VXDCA	Four Versus Unknown Number Defensive Counter Air flight	1
513	LAT flight (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
613	ACM QUAL (see USMC F-18 T&R Manual, NAVMC 3500.50)	1
AAR	Air to Air Refueling flight	N/A
ACT	Air Combat Tactics flight	12
ADEX	Air Defense Exercise flight	6
AIC (AI)	Air Interdiction flight	13
AIRNAV	Airways Navigation flight	14
AR	Armed Reconnaissance flight	2
CHASE	Chase aircraft during test flight	1
CURRENCY	Recertifies currency for specific mission code	3

DAS	Deep Air Support flight	2
DCA	Defensive Counter Air flight	13
DEMO	Demonstration flight such as air show	19
FAC(A)	Forward Air Controller (Airborne) flight	14
FAWI	FRS All-Weather Intercept flight, USN-specific code	65
FBFM	FRS Basic Fighter Maneuvers flight, USN-specific code	409
FCQL	FRS Carrier Qualification flight, USN-specific code	121
FFRM	FRS Formation flight, USN-specific code	22
FFWT	FRS Fighter Weapons Tactics flight, USN-specific code	261
FIFR	FRS Instrument Flight Rules flight, USN-specific code	3
FLYOFF	Fly-off flight from ship to shore	14
FLYON	Fly-on flight from shore to ship	8
FLYOVER	Supersonic flyover demonstration	2
FNAT	FRS Night Low Altitude flight, USN-specific code	8
FNVG	FRS Night Vision Goggle flight, USN-specific code	33
FOCF	FRS Out-of-Control Flight, USN-specific code	8
FSRA	FRS Section Radar Attack flight, USN-specific code	74
FWT	Fighter Weapons Tactics flight	9
LAHD	Low Angle High Drag flight, USN-specific code	7
LFE	Large Force Exercise flight	N/A
PMCF	Post Maintenance Check Flight	2
PRO	Proficiency flight	35
REDAIR	Foreign Profile Air-to-Air flight	361
SCAR	Strike Coordination and Reconnaissance	8
SEM	Section Engaged Maneuvering, USN-specific code	9
SF-1	Section Flight Air-to-Ground, USN-specific code	17
SF-2	Section Flight Air-to-Ground, USN-specific code	13
SF-3	Section Flight Air-to-Ground, USN-specific code	13
SF-4	Section Flight Air-to-Ground, USN-specific code	7
SF-6	Section Flight Surface-to-Air Counter Tactics, USN-specific code	22
SF-7	Section Flight Air-to-Ground, USN-specific code	14
SF-10	Section Flight Air-to-Air, USN-specific code	17
SF-11	Section Flight Air-to-Air, USN-specific code	12
SUPT	Ship Support – a profile that simulates a missile inbound to a ship	93
SWEEP	Area sweep to remove air threats in support of a strike package	3
SXNMAN	Section Maneuvers flight	4
TAR	Tactical Aerial Reconnaissance flight	N/A
WU	Warm-Up flight	4

APPENDIX B

Table 8. Data set columns not used for modeling

Header	Column Description	Reason for Omission
Study Group	References FLE Study Group - Fleet, FRS and Weapons and Tactics Instructor course	There is no pertinent difference between study groups
Squadron	USN or USMC squadron contributing to the record	USN and USMC squadrons are assumed to fly the same profiles
Buno	Bureau number of the F-18	The bureau number is for record keeping and is not useful for modeling purposes
Date	Sortie date	The date of the flight provides no useful modeling data
cMODEX	Three digit serial number for USN and USMC aircraft	The aircraft identifier is for record keeping and is not useful for modeling purposes
FlightDocNum	NAVFLIR number	Does not contribute for FLE modeling purposes
TypeMission	USN or USMC TMC	Used for grouping purposes – many records were blank.
TypeMissionA	USN or USMC TMC	Most records were blank
TypeMissionB	USN or USMC TMC (used for flights that qualified for more than one MTC)	Most records were blank
FlightHour	Flight time entered on NAVFLIR	Subject to human error and extreme variablity
cDepartTime	Flight departure time	Time of day does not affect FLE
cReturnTime	Flight return time	Time of day does not affect FLE
cADFName	Multiple DSU file data set name	NAVAIR record-keeping purposes only
cMUFile	DSU record file name from NAVAIR	NAVAIR record-keeping purposes only
ciniNum	The initialization number of the flight within the MU file.	NAVAIR record-keeping purposes only
cMCL	The mission computer load of the aircraft	NAVAIR record-keeping purposes only

WFTrigCnt	Wing-fold trigger count	USMC disregards wing-fold FLE due to WRFLE being the driving metric
dWF	NAVAIR wing-fold FLE number	USMC disregards wing-fold FLE due to WRFLE being the driving metric
dWRr	WRFLE rate	WRFLE rate is a function of dWR so it cannot be used to predict
DWFr	Wing-fold FLE rate	A function of dWF (see dWF)

APPENDIX C

A. AA

1. Coefficients

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0319	0.0080	-4.0116	0.0001
TypeB	0.0145	0.0133	1.0920	0.2752
TypeC	0.0095	0.0058	1.6464	0.1001
TypeD	-0.0073	0.0103	-0.7027	0.4825
CL	0.0256	0.0079	3.2435	0.0012
rDHCnt	0.0143	0.0065	2.2188	0.0268
WRTrigCnt	0.0003	0.0000	6.4470	0.0000
rNzMax	0.1325	0.0141	9.4137	0.0000
rNzMin	0.0236	0.0387	0.6104	0.5418
I(dWRFill^0.25)	0.0626	0.0720	0.8686	0.3853
Left	-0.0330	0.0121	-2.7314	0.0065
Right	0.0020	0.0012	1.6091	0.1080
TypeBI(dWRFill^0.25)	0.2246	0.0907	2.4765	0.0135
TypeCI(dWRFill^0.25)	0.1179	0.0337	3.4991	0.0005
TypeDI(dWRFill^0.25)	0.2254	0.0580	3.8867	0.0001
WRTrigCnt:rNzMin	0.0007	0.0002	3.1493	0.0017
TypeBrNzMax	-0.0425	0.0214	-1.9835	0.0477
TypeCrNzMax	-0.0235	0.0089	-2.6541	0.0081
TypeDrNzMax	-0.0172	0.0156	-1.1040	0.2700
rNzMax:Left	0.0191	0.0087	2.1963	0.0284
TypeBCL	-0.0081	0.0056	-1.4480	0.1481
TypeCCL	-0.0075	0.0033	-2.3000	0.0217
TypeDCL	-0.0104	0.0035	-2.9538	0.0032
WRTrigCnt:I(dWRFill^0.25)	-0.0005	0.0003	-1.8991	0.0580
rDHCnt:rNzMax	-0.0506	0.0126	-4.0105	0.0001
rDHCnt:I(dWRFill^0.25)	0.2684	0.0641	4.1878	0.0000
rNzMin:I(dWRFill^0.25)	-0.9070	0.3435	-2.6403	0.0085
rDHCnt:WRTrigCnt	0.0000	0.0000	-1.9485	0.0517
CL:rDHCnt	-0.0232	0.0078	-2.9671	0.0031
rDHCnt:Left	0.0202	0.0083	2.4298	0.0154

Table 9. Coefficients for final AA model

B. AAW

1. Final Model

$dWR^{0.25} \sim Type + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Left + Right + rNzMin{:}dWRFill^{0.25} + rDHCnt{:}rNzMax + rDHCnt{:}dWRFill^{0.25} +$

Type:rDHCnt + *rNzMin:Right* + *rNzMin:Left* + *dWRFill* $^{0.25}$*:Right* + *rNzMax:Right* + *WRTrigCnt:Right*

2. Model Comparisons

	No Interactions	Interactions
R^2 Adjusted	0.9243	0.932
RSE	0.0086	0.0082
Cross-Validation (30 reps)	N/A	0.0086

Table 10. AAW model comparisons

3. Type III SS ANOVA

Table 11. ANOVA table for AAW with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	1	1.27e-4	1.27e-4	1.87	0.173
rDHCnt	1	9.76e-5	9.76e-5	1.43	0.232
WRTrigCnt	1	0.00339	0.00339	49.8	0.0
rNzMax	1	0.00203	0.00203	29.8	0.0
rNzMin	1	0.00118	0.00118	17.4	4.03e-5
$dWRFill^{0.25}$	1	0.00196	0.00196	28.7	0.0
Left	1	9.73e-6	9.73e-6	0.143	0.706
Right	1	1.27e-4	1.27e-4	1.86	0.173
$rNzMin:dWRFill^{0.25}$	1	7.15e-4	7.15e-4	10.5	0.00132
rDHCnt:rNzMax	1	3.27e-4	3.27e-4	4.81	0.0291
$rDHCnt:dWRFill^{0.25}$	1	1.52e-4	1.52e-4	2.24	0.136
Type:rDHCnt	1	2.58e-4	2.58e-4	3.79	0.0526
rNzMin:Right	1	4.22e-4	4.22e-4	6.19	0.0134
rNzMin:Left	1	2.87e-4	2.87e-4	4.21	0.041
$dWRFill^{0.25}:Right$	1	5.6e-4	5.6e-4	8.22	0.00443
rNzMax:Right	1	3.12e-4	3.12e-4	4.58	0.0331
WRTrigCnt:Right	1	1.6e-4	1.6e-4	2.35	0.126
Residuals	308	0.021	6.81e-5	NA	NA

4. Coefficients

Table 12. Coefficients for final AAW model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0251	0.0116	-2.1698	0.0308
Type	0.0072	0.0053	1.3671	0.1726
rDHCnt	0.0145	0.0080	1.8099	0.0713
WRTrigCnt	0.0001	0.0000	3.5790	0.0004
rNzMax	0.0855	0.0202	4.2388	0.0000
rNzMin	-0.2364	0.0608	-3.8905	0.0001
I(dWRFill^0.25)	0.4825	0.0830	5.8165	0.0000
Left	-0.0006	0.0015	-0.3779	0.7057
Right	-0.0180	0.0132	-1.3652	0.1732
rNzMin:I(dWRFill^0.25)	1.2262	0.3784	3.2407	0.0013
rDHCnt:rNzMax	-0.0336	0.0153	-2.1924	0.0291
rDHCnt:I(dWRFill^0.25)	0.1034	0.0692	1.4954	0.1358
Type:rDHCnt	-0.0092	0.0047	-1.9461	0.0526
rNzMin:Right	-0.0765	0.0308	-2.4884	0.0134
rNzMin:Left	0.0773	0.0377	2.0525	0.0410
I(dWRFill^0.25):Right	-0.1481	0.0516	-2.8672	0.0044
rNzMax:Right	0.0352	0.0165	2.1409	0.0331
WRTrigCnt:Right	0.0001	0.0000	1.5329	0.1263

C. AS

1. Final Model

$dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + dWRFill^{0.25} + Type{:}WRTrigCnt + rDHCnt{:}rNzMax$

2. Model Comparisons

Table 13. AS model comparisons

	No Interactions	Interactions
R^2 Adjusted	0.9551	0.9628
RSE	0.0089	0.0081
Cross-Validation (30 reps)	N/A	0.0080

3. Type III SS ANOVA

Table 14. ANOVA table for AS with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	1	6.65e-4	6.65e-4	10.1	0.00206
CL	1	1.71e-4	1.71e-4	2.59	0.111
rDHCnt	1	1.72e-4	1.72e-4	2.61	0.11
WRTrigCnt	1	0.00137	0.00137	20.8	1.7e-5
rNzMax	1	0.00191	0.00191	28.9	0.0
$dWRFill^{0.25}$	1	0.0105	0.0105	160.0	0.0
Type:WRTrigCnt	1	9.81e-4	9.81e-4	14.9	2.19e-4
rDHCnt:rNzMax	1	2.95e-4	2.95e-4	4.48	0.0373
Residuals	86	0.00566	6.59e-5	NA	NA

4. Coefficients

Table 15. Coefficients for final AS model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0671	0.0204	-3.2901	0.0015
Type	-0.0181	0.0057	-3.1784	0.0021
CL	0.0145	0.0090	1.6094	0.1112
rDHCnt	0.0311	0.0193	1.6145	0.1101
WRTrigCnt	0.0000	0.0000	1.7555	0.0827
rNzMax	0.1517	0.0282	5.3805	0.0000
I(dWRFill^0.25)	0.5229	0.0413	12.6531	0.0000
Type:WRTrigCnt	0.0003	0.0001	3.8596	0.0002
rDHCnt:rNzMax	-0.0530	0.0251	-2.1158	0.0373

D. CAS

1. Final Model

$dWR^{0.25} \sim Type + rDHCnt + WRTrigCnt + rNzMax + dWRFill^{0.25} + WRTrigCnt{:}rNzMax + rDHCnt{:}WRTrigCnt + Type{:}rNzMax$

2. Model Comparisons

Table 16. CAS model comparisons

	No Interactions	Interactions
R^2 Adjusted	0.9429	0.948

RSE	0.0085	0.0081
Cross-Validation (30 reps)	N/A	0.0085

3. Type III SS ANOVA

Table 17. ANOVA table for CAS with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	1	2.35e-4	2.35e-4	3.55	0.0615
rDHCnt	1	1.32e-4	1.32e-4	1.99	0.161
WRTrigCnt	1	1.25e-8	1.25e-8	1.88e-4	0.989
rNzMax	1	0.00224	0.00224	33.7	0.0
$dWRFill^{0.25}$	1	0.0133	0.0133	201.0	0.0
WRTrigCnt:rNzMax	1	3.26e-4	3.26e-4	4.92	0.028
rDHCnt:WRTrigCnt	1	2.96e-4	2.96e-4	4.46	0.0363
Type:rNzMax	1	1.36e-4	1.36e-4	2.04	0.155
Residuals	155	0.0103	6.64e-5	NA	NA

4. Coefficients

Table 18. Coefficients for final CAS model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0083	0.0067	-1.2428	0.2158
Type	-0.0185	0.0098	-1.8834	0.0615
rDHCnt	0.0035	0.0025	1.4098	0.1606
WRTrigCnt	0.0000	0.0001	-0.0137	0.9891
rNzMax	0.0510	0.0086	5.9499	0.0000
I(dWRFill^0.25)	0.5128	0.0362	14.1748	0.0000
WRTrigCnt:rNzMax	0.0003	0.0001	2.2178	0.0280
rDHCnt:WRTrigCnt	-0.0001	0.0000	-2.1123	0.0363
Type:rNzMax	0.0162	0.0113	1.4299	0.1548

E. FAM

1. Coefficients

Table 19. Coefficients for final FAM model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	0.0020	0.0045	0.4530	0.6510
Type	-0.0061	0.0035	-1.7322	0.0846
rDHCnt	-0.0032	0.0018	-1.7976	0.0736
WRTrigCnt	0.0000	0.0001	-0.4824	0.6300
rNzMax	0.0384	0.0066	5.8046	0.0000

rNzMin	-0.1807	0.0905	-1.9975	0.0470
I(dWRFill^0.25)	0.5797	0.0542	10.7014	0.0000
Right	0.0137	0.0076	1.7949	0.0740
rNzMin:I(dWRFill^0.25)	3.0699	0.7009	4.3801	0.0000
WRTrigCnt:I(dWRFill^0.25)	0.0013	0.0005	2.7217	0.0070
WRTrigCnt:rNzMin	-0.0017	0.0008	-2.2096	0.0281
Type:I(dWRFill^0.25)	0.0674	0.0335	2.0130	0.0453
rDHCnt:rNzMin	-0.0835	0.0586	-1.4247	0.1556

F. FCF

1. Coefficients

Table 20. Coefficients for final FCF model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	0.0038	0.0070	0.5484	0.5895
Type	-0.0288	0.0074	-3.8915	0.0009
CL	-0.0045	0.0017	-2.6030	0.0170
WRTrigCnt	0.0003	0.0001	4.5672	0.0002
rNzMax	0.0257	0.0116	2.2075	0.0391
rNzMin	-0.5069	0.1138	-4.4531	0.0002
I(dWRFill^0.25)	0.5705	0.0662	8.6147	0.0000
rNzMin:I(dWRFill^0.25)	3.0730	0.9229	3.3297	0.0033
Type:WRTrigCnt	0.0003	0.0001	2.6955	0.0139

G. FCLP

1. Final Model

$dWR^{0.25} \sim rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + rDHCnt{:}WRTrigCnt + WRTrigCnt{:}rNzMin + WRTrigCnt{:}dWRFill^{0.25} + rNzMax{:}dWRFill^{0.25}$

2. Model Comparisons

Table 21. FCLP model comparisons

	No Interactions	**Interactions**
R^2 **Adjusted**	0.9761	0.9789
RSE	0.0051	0.0048
Cross-Validation (30 reps)	N/A	0.0051

3. Type III SS ANOVA

Table 22. ANOVA table for FCLP with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
rDHCnt	1	1.03e-4	1.03e-4	4.55	0.0345
WRTrigCnt	1	3.67e-5	3.67e-5	1.62	0.205
rNzMax	1	7.92e-4	7.92e-4	34.9	0.0
rNzMin	1	2.59e-4	2.59e-4	11.4	9.17e-4
$dWRFill^{0.25}$	1	0.00681	0.00681	300.0	0.0
rDHCnt:WRTrigCnt	1	2.02e-4	2.02e-4	8.91	0.00325
WRTrigCnt:rNzMin	1	3.7e-4	3.7e-4	16.3	8.21e-5
$WRTrigCnt{:}dWRFill^{0.25}$	1	1.55e-4	1.55e-4	6.81	0.00987
$rNzMax{:}dWRFill^{0.25}$	1	1.16e-4	1.16e-4	5.09	0.0254
Residuals	170	0.00386	2.27e-5	NA	NA

4. Coefficients

Table 23. Coefficients for final FCLP model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0096	0.0023	-4.2434	0.0000
rDHCnt	0.0011	0.0005	2.1319	0.0345
WRTrigCnt	0.0002	0.0001	1.2714	0.2053
rNzMax	0.0410	0.0069	5.9067	0.0000
rNzMin	-0.1436	0.0426	-3.3743	0.0009
I(dWRFill^0.25)	0.7285	0.0421	17.3245	0.0000
rDHCnt:WRTrigCnt	-0.0002	0.0001	-2.9856	0.0032
WRTrigCnt:rNzMin	0.0039	0.0010	4.0358	0.0001
WRTrigCnt:I(dWRFill^0.25)	0.0028	0.0011	2.6096	0.0099
rNzMax:I(dWRFill^0.25)	-0.1786	0.0792	-2.2557	0.0254

H. FERRY

The Ferry model contains a linear feature on the residuals versus fitted values plot due to instances of dWR equal to zero. These records are acceptable outcomes of the Ferry flight profile and are retained in the model despite violating the continuous data assumption.

1. Final Model

$dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + dWRFill^{0.25} + Left + WRTrigCnt{:}rNzMax + WRTrigCnt{:}dWRFill^{0.25} + CL{:}WRTrigCnt + Type{:}rDHCnt + CL{:}rDHCnt$

2. Model Comparisons

Table 24. FERRY model comparisons

	No Interactions	Interactions
R^2 Adjusted	0.9576	0.9677
RSE	0.0048	0.0043
Cross-Validation (30 reps)	N/A	0.0046

3. Type III SS ANOVA

Table 25. ANOVA table for FERRY with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	1	2.7e-5	2.7e-5	1.5	0.226
CL	1	1.06e-6	1.06e-6	0.0585	0.81
rDHCnt	1	1.35e-5	1.35e-5	0.75	0.39
WRTrigCnt	1	6.5e-5	6.5e-5	3.6	0.062
rNzMax	1	1.6e-5	1.6e-5	0.884	0.35
$\mathrm{dWRFill}^{0.25}$	1	0.00324	0.00324	180	0
Left	1	5.71e-5	5.71e-5	3.16	0.0799
WRTrigCnt:rNzMax	1	2.78e-4	2.78e-4	15.4	2.07e-4
$\mathrm{WRTrigCnt{:}dWRFill}^{0.25}$	1	9.69e-5	9.69e-5	5.37	0.0236
CL:WRTrigCnt	1	6.08e-5	6.08e-5	3.37	0.0709
Type:rDHCnt	1	6.74e-5	6.74e-5	3.73	0.0576
CL:rDHCnt	1	3.33e-5	3.33e-5	1.84	0.179
Residuals	67	0.00121	1.81e-5	NA	NA

4. Coefficients

Table 26. Coefficients for final FERRY model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0047	0.0038	-1.2281	0.2237
Type	0.0035	0.0028	1.2230	0.2256
CL	0.0009	0.0039	0.2419	0.8096
rDHCnt	0.0009	0.0013	0.7141	0.4776
WRTrigCnt	-0.0008	0.0006	-1.2772	0.2059
rNzMax	0.0073	0.0078	0.9403	0.3504
I(dWRFill^0.25)	0.7809	0.0583	13.3990	0.0000
Left	-0.0029	0.0016	-1.7784	0.0799
WRTrigCnt:rNzMax	0.0080	0.0020	3.9250	0.0002
WRTrigCnt:I(dWRFill^0.25)	-0.0422	0.0182	-2.3164	0.0236
CL:WRTrigCnt	-0.0007	0.0004	-1.8353	0.0709
Type:rDHCnt	-0.0032	0.0016	-1.9317	0.0576

```
CL:rDHCnt    0.0026    0.0019     1.3576    0.1792
```

I. LAT

1. Final Model

$dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Type{:}CL + rDHCnt{:}WRTrigCnt + Type{:}rDHCnt + Type{:}rNzMax + CL{:}rDHCnt + CL{:}dWRFill^{0.25}$

2. Model Comparisons

Table 27. LAT model comparisons

	No Interactions	**Interactions**
R^2 **Adjusted**	0.9455	0.9725
RSE	0.0071	0.0054
Cross-Validation (30 reps)	N/A	0.0065

3. Type III SS ANOVA

Table 28. ANOVA table for LAT with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	1	2.2e-4	2.2e-4	7.56	0.00839
CL	1	2.55e-4	2.55e-4	8.75	0.0048
rDHCnt	1	1.77e-5	1.77e-5	0.609	0.439
WRTrigCnt	1	4.56e-4	4.56e-4	15.6	2.52e-4
rNzMax	1	0.00117	0.00117	40.0	0.0
rNzMin	1	6.99e-4	6.99e-4	24.0	1.14e-5
$dWRFill^{0.25}$	1	9.56e-4	9.56e-4	32.8	0.0
Type:CL	1	5.06e-4	5.06e-4	17.4	1.28e-4
rDHCnt:WRTrigCnt	1	1.46e-4	1.46e-4	5.01	0.0299
Type:rDHCnt	1	2.42e-4	2.42e-4	8.31	0.00588
Type:rNzMax	1	1.47e-4	1.47e-4	5.05	0.0293
CL:rDHCnt	1	2.37e-4	2.37e-4	8.12	0.00644
$CL:dWRFill^{0.25}$	1	3.1e-4	3.1e-4	10.6	0.00205
Residuals	48	0.0014	2.91e-5	NA	NA

4. Coefficients

Table 29. Coefficients for final LAT model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	0.0250	0.0180	1.3895	0.1711
Type	-0.0718	0.0290	-2.4786	0.0168
CL	0.0612	0.0183	3.3410	0.0016
rDHCnt	-0.0125	0.0079	-1.5878	0.1189
WRTrigCnt	0.0003	0.0001	3.9538	0.0003
rNzMax	0.0493	0.0133	3.6925	0.0006
rNzMin	-0.1091	0.0223	-4.8993	0.0000
I(dWRFill^0.25)	0.3967	0.0436	9.1082	0.0000
Type:CL	-0.0144	0.0035	-4.1664	0.0001
rDHCnt:WRTrigCnt	-0.0002	0.0001	-2.2373	0.0299
Type:rDHCnt	0.0324	0.0112	2.8832	0.0059
Type:rNzMax	0.0543	0.0242	2.2470	0.0293
CL:rDHCnt	-0.0238	0.0084	-2.8493	0.0064
CL:I(dWRFill^0.25)	-0.2607	0.0800	-3.2606	0.0020

J. NS

1. Final Model

$dWR^{0.25} \sim WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Right + WRTrigCnt{:}rNzMin + WRTrigCnt{:}rNzMax + dWRFill^{0.25}{:}Right$

2. Model Comparisons

Table 30. NS model comparisons

	No Interactions	Interactions
R^2 **Adjusted**	0.9398	0.9642
RSE	0.0077	0.0058
Cross-Validation (30 reps)	N/A	0.0072

3. Type III SS ANOVA

Table 31. ANOVA table for NS with interaction terms

Terms	**Df**	**SS**	**Mean Sq**	**F Value**	**Pr(F)**
WRTrigCnt	1	2.06e-4	2.06e-4	6.07	0.0217
rNzMax	1	8.17e-6	8.17e-6	0.241	0.628
rNzMin	1	5.1e-4	5.1e-4	15.0	7.62e-4
$dWRFill^{0.25}$	1	6.32e-4	6.32e-4	18.6	2.55e-4
Right	1	1.83e-4	1.83e-4	5.4	0.0294
WRTrigCnt:rNzMin	1	3.98e-4	3.98e-4	11.7	0.00231
WRTrigCnt:rNzMax	1	2.64e-4	2.64e-4	7.78	0.0104
$dWRFill^{0.25}$:Right	1	1.27e-4	1.27e-4	3.75	0.0652
Residuals	23	7.8e-4	3.39e-5	NA	NA

4. Coefficients

Table 32. Coefficients for final NS model

	Value	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	0.0269	0.0187	1.4404	0.1632
WRTrigCnt	-0.0013	0.0005	-2.4632	0.0217
rNzMax	0.0122	0.0248	0.4908	0.6282
rNzMin	-1.0895	0.2810	-3.8778	0.0008
I(dWRFill^0.25)	0.4972	0.0613	8.1069	0.0000
Right	0.0449	0.0193	2.3229	0.0294
WRTrigCnt:rNzMin	0.0155	0.0045	3.4261	0.0023
WRTrigCnt:rNzMax	0.0018	0.0006	2.7893	0.0104
I(dWRFill^0.25):Right	-0.2742	0.1416	-1.9364	0.0652

K. STK

1. Final Model

$dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + dWRFill^{0.25} + WRTrigCnt{:}dWRFill^{0.25} + Type{:}CL + Type{:}rDHCnt$

2. Model Comparisons

Table 33. STK model comparisons

	No Interactions	Interactions
R^2 Adjusted	0.9349	0.9386
RSE	0.0095	0.0092
Cross-Validation (30 reps)	N/A	0.0094

3. Type III SS ANOVA

Table 34. ANOVA table for STK with interaction terms

Terms	Df	SS	Mean Sq	F Value	Pr(F)
Type	1	1.61e-4	1.61e-4	1.89	0.171
CL	1	5.92e-4	5.92e-4	6.92	0.00903
rDHCnt	1	5.19e-4	5.19e-4	6.07	0.0144
WRTrigCnt	1	0.00367	0.00367	43.0	0.0
rNzMax	1	0.00665	0.00665	77.8	0.0
$dWRFill^{0.25}$	1	0.0192	0.0192	224.0	0.0
$WRTrigCnt{:}dWRFill^{0.25}$	1	4.91e-4	4.91e-4	5.74	0.0173
Type:CL	1	4.44e-4	4.44e-4	5.2	0.0234
Type:rDHCnt	1	4.35e-4	4.35e-4	5.08	0.025
Residuals	258	0.0221	8.55e-5	NA	NA

4. Coefficients

Table 35. Coefficients for final STK model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0147	0.0055	-2.6639	0.0082
Type	-0.0083	0.0043	-1.9049	0.0579
CL	-0.0065	0.0014	-4.5942	0.0000
rDHCnt	-0.0078	0.0023	-3.3521	0.0009
WRTrigCnt	0.0003	0.0000	6.5555	0.0000
rNzMax	0.0677	0.0077	8.8180	0.0000
I(dWRFill^0.25)	0.5583	0.0373	14.9775	0.0000
WRTrigCnt:I(dWRFill^0.25)	-0.0007	0.0003	-2.3967	0.0173
Type:CL	0.0058	0.0026	2.2798	0.0234
Type:rDHCnt	0.0074	0.0033	2.2545	0.0250

L. ENTIRE DATA SET

1. Final Model

$dWR^{0.25} \sim Type + CL + rDHCnt + WRTrigCnt + rNzMax + rNzMin + dWRFill^{0.25} + Left + Right + Type{:}dWRFill^{0.25} + rDHCnt{:}rNzMax + CL{:}dWRFill^{0.25} + Type{:}Right + Type{:}rNzMax + WRTrigCnt{:}Left + WRTrigCnt{:}rNzMin + rNzMin{:}Right + Type{:}WRTrigCnt + Left{:}Right + dWRFill^{0.25}{:}Left + WRTrigCnt{:}rNzMax + WRTrigCnt{:}dWRFill^{0.25} + rDHCnt{:}Left + rNzMin{:}Left + CL{:}rNzMin + rDHCnt{:}rNzMin$

2. Model Comparisons

Table 36. Entire data set model comparisons

	No Interactions	Interactions
R^2 Adjusted	0.9489	0. 953
RSE	0.0087	0.0084
Cross-Validation (30 reps)	N/A	0.0080

3. Type III SS ANOVA

Table 37. ANOVA table for entire data set with interaction terms

Terms	**Df**	**SS**	**Mean Sq**	**F Value**	**Pr(F)**
Type	3	2.81e-4	9.35e-5	1.33	0.264
CL	1	4.09e-4	4.09e-4	5.8	0.0161
rDHCnt	1	5.18e-5	5.18e-5	0.735	0.391
WRTrigCnt	1	6.08e-4	6.08e-4	8.63	0.00335
rNzMax	1	0.00806	0.00806	114.0	0.0
rNzMin	1	0.00123	0.00123	17.5	2.96e-5
$dWRFill^{0.25}$	1	0.0265	0.0265	375.0	0.0
Left	1	2.35e-4	2.35e-4	3.33	0.0681
Right	1	9.11e-4	9.11e-4	12.9	3.32e-4
Type:$dWRFill^{0.25}$	3	0.00503	0.00168	23.8	0.0
rDHCnt:rNzMax	1	6.89e-4	6.89e-4	9.77	0.00179
CL:$dWRFill^{0.25}$	1	9.82e-4	9.82e-4	13.9	1.94e-4
Type:Right	3	0.00176	5.87e-4	8.33	1.66e-5
Type:rNzMax	3	0.00176	5.85e-4	8.3	1.72e-5
WRTrigCnt:Left	1	7.01e-4	7.01e-4	9.94	0.00164
WRTrigCnt:rNzMin	1	6.59e-4	6.59e-4	9.35	0.00226
rNzMin:Right	1	4.31e-4	4.31e-4	6.12	0.0135
Type:WRTrigCnt	3	5.44e-4	1.81e-4	2.58	0.0523
Left:Right	1	4.04e-4	4.04e-4	5.74	0.0167
$dWRFill^{0.25}$:Left	1	3.53e-4	3.53e-4	5.01	0.0253
WRTrigCnt:rNzMax	1	6.66e-4	6.66e-4	9.44	0.00214
WRTrigCnt:$dWRFill^{0.25}$	1	3.07e-4	3.07e-4	4.35	0.0371
rDHCnt:Left	1	2.21e-4	2.21e-4	3.14	0.0765
rNzMin:Left	1	3.33e-4	3.33e-4	4.73	0.0298
CL:rNzMin	1	1.66e-4	1.66e-4	2.35	0.125
rDHCnt:rNzMin	1	1.47e-4	1.47e-4	2.08	0.15
Residuals	2180	0.154	7.05e-5	NA	NA

4. Coefficients

Table 38. Coefficients for entire data set model

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.0164	0.0041	-4.0319	0.0001
TypeB	0.0036	0.0090	0.3992	0.6898
TypeC	0.0038	0.0038	0.9958	0.3195
TypeD	0.0032	0.0041	0.7899	0.4297
CL	0.0030	0.0013	2.4091	0.0161
rDHCnt	0.0026	0.0010	2.5816	0.0099
WRTrigCnt	0.0001	0.0000	2.4643	0.0138
rNzMax	0.0803	0.0071	11.3143	0.0000
rNzMin	-0.0806	0.0219	-3.6797	0.0002
I(dWRFill^0.25)	0.3562	0.0353	10.1014	0.0000
Left	0.0034	0.0028	1.1784	0.2388
Right	0.0232	0.0054	4.3055	0.0000
TypeBI(dWRFill^0.25)	0.1685	0.0838	2.0102	0.0445
TypeCI(dWRFill^0.25)	0.2604	0.0353	7.3726	0.0000
TypeDI(dWRFill^0.25)	0.3213	0.0386	8.3234	0.0000
rDHCnt:rNzMax	-0.0050	0.0016	-3.1263	0.0018
CL:I(dWRFill^0.25)	-0.0449	0.0120	-3.7333	0.0002
TypeBRight	-0.0123	0.0109	-1.1345	0.2567
TypeCRight	-0.0244	0.0052	-4.7096	0.0000
TypeDRight	-0.0225	0.0053	-4.2434	0.0000
TypeBrNzMax	-0.0253	0.0165	-1.5300	0.1262
TypeCrNzMax	-0.0297	0.0068	-4.3516	0.0000
TypeDrNzMax	-0.0366	0.0074	-4.9593	0.0000
WRTrigCnt:Left	0.0000	0.0000	3.1526	0.0016
WRTrigCnt:rNzMin	0.0004	0.0001	3.0574	0.0023
rNzMin:Right	-0.0422	0.0170	-2.4736	0.0135
TypeBWRTrigCnt	0.0000	0.0000	0.5775	0.5637
TypeCWRTrigCnt	0.0000	0.0000	-1.6782	0.0935
TypeDWRTrigCnt	-0.0001	0.0000	-2.3407	0.0193
Left:Right	0.0040	0.0017	2.3955	0.0167
I(dWRFill^0.25):Left	-0.0441	0.0197	-2.2380	0.0253
WRTrigCnt:rNzMax	0.0001	0.0000	3.0731	0.0021
WRTrigCnt:I(dWRFill^0.25)	-0.0003	0.0002	-2.0857	0.0371
rDHCnt:Left	-0.0029	0.0016	-1.7723	0.0765
rNzMin:Left	0.0410	0.0188	2.1745	0.0298
CL:rNzMin	-0.0254	0.0166	-1.5328	0.1255
rDHCnt:rNzMin	0.0244	0.0169	1.4417	0.1495

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